Document 5

ACOUSTIC-TRAWL SURVEYS OF PACIFIC SARDINE (*SARDINOPS SAGAX*) IN THE CALIFORNIA CURRENT ECOSYSTEM

Prepared for
WORKSHOP ON ENHANCING STOCK ASSESSMENTS OF PACIFIC SARDINE IN THE CALIFORNIA CURRENT THROUGH COOPERATIVE SURVEYS
June 1-3, 2010
La Jolla, California

David A. Demer, Juan P. Zwolinski, Kyle A. Byers, George R. Cutter, Josiah S. Renfree, and Thomas S. Sessions
Advanced Survey Technologies Program
Southwest Fisheries Science Center
8604 La Jolla Shores Drive
La Jolla, CA, 92037
david.demer@noaa.gov

I. Introduction and Background of Survey Method

1. Theoretical basis and assumptions

Acoustic-trawl methods have been used to survey Pacific sardine (*Sardinops sagax*), hereafter sardine, off the west coast of the United States of America (US), within the California Current Ecosystem (CCE), for more than a half century. Beginning with 'sonar mapping' in the 1950's (Smith, 1978), and single-frequency echo-sounding in the 1960's (Mais, 1977), the survey equipment and methods evolved to broad bandwidth resonance scattering in the 1970's (Holliday, 1972), and now to a combination of multiple-frequency scientific echosounders and multi-beam sonars (e.g., Cutter and Demer, 2008). Multi-frequency echosounders are used to record acoustic backscatter data along parallel-line transects spanning the sardine habitat. Net catch information is used to ascribed these data to the variety of sound scatterers present in the CCE, for example: sardine and other coastal pelagic fish species (CPS); and krill (euphausiid spp.). The total backscatter from sardine is divided by the backscatter representative of an individual sardine to estimate and map sardine-biomass density. Sardine biomass is estimated by multiplying the mean biomass density by the survey area. Total uncertainty, including random and systematic components of measurement and sampling error, is then estimated. Random error is dominated by sampling (Demer, 2004). Systematic sampling and measurement error can result from temporally- and spatially-varying biases associated with fish behavior, species identification, and estimation of the mean backscatter from and individual sardine. Data from a multibeam sonar helps to quantify some of these errors and further refine the acoustic-trawl method (Cutter and Demer, 2008). A broad bandwidth multibeam sonar (Simrad ME70), installed on the new NOAA fisheries survey vessels, may prove to be the next generation of instrument used in acoustic-trawl surveys of fish and zooplankton (Demer *et al*., in prep.).

2. Objectives of application

The principal objectives of acoustic-trawl surveys are to estimate the geographic distributions and biomasses of target and coexisting species. Additional objectives may include, for example, investigations of: causal relationships between targets with their biotic and abiotic environments; predator-prey interactions; and vertical distributions.

3. Pros and Cons of method

Acoustic sampling can be conducted continuously while the survey vessel is underway. It provides high-resolution, quantitative information about the distributions, densities, and interactions of the various species in the survey area. It is therefore a highly efficient tool for concurrent sampling of many trophic levels. The principal challenges of acoustic surveys are to estimate and survey the potential sardine habitat (habitat estimation); identify the contribution of sardine to the total acoustic backscatter (species identification); and to estimate the mean acoustic backscatter per individual sardine (target strength estimation). Net catch information is used to address each of these challenges. While there are continuous efforts to improve the accuracies of acoustic-trawl surveys, the resulting biomass estimates are generally within ten to twenty percent of their respective stock assessments. Such accuracy, precision, and efficiency has made acoustic-trawl the preferred method for monitoring and assessing fish stocks around the globe.

II. Design for Survey in the CA Current

1. Spatial Coverage

To minimize uncertainties in estimates of sardine biomass, irrespective of the survey technique, the sampling effort must be optimally allocated to only the region containing the stock. Zwolinski *et al.* (submitted) demonstrated accurate predictions of total sardine habitat and its dynamics. Based on a 12-year dataset including samples of sardine eggs and concomitant remotely-sensed oceanographic conditions, a probabilistic, generalized-additive model (GAM; Wood, 2006) was developed which predicts the spatial-temporal distributions of habitat for the northern stock of sardine. Significant relationships were identified between sardine eggs and sea-surface temperature (SST), chlorophyll-a concentration (CHL), and the gradient of the sea-surface altitude (GRAD). The model describes and accurately predicts the habitat and seasonal migration pattern of sardine, whether or not they are spawning (**Fig. 1**; Zwolinski *et al.*, submitted). The model predictions of potential habitat were extensively validated by fishery landing data from Oregon, Washington, and British Columbia, and scientific net sample data collected near the Columbia River mouth. The predicted habitat can be used to optimize the times and locations of DEPM, acoustic-trawl, and aerial surveys of Pacific sardine. Averaged over twelve years, 92 % of the biomass was sampled using 64 % of the original survey effort. That is, habitat predictions could have allowed approximately 36 % of the survey effort to be reallocated to potential habitat, likely reducing the sampling error.

2. Temporal Coverage

Zwolinski *et al*. (submitted) concluded that sardine surveys may be most efficiently conducted during the months of June and July, when the habitat is compressed along the coasts of Oregon and Washington, the fish are generally north of Point Conception and south of the Strait of Juan de Fuca, the days are longest and thus daytime sampling is maximized, and the survey can be augmented with fishery catch data from the same general time and place.

3. Statistical sampling protocols

Sardine biomass is patchy, and most of its biomass is aggregated in sparsely-distributed dense schools (Cutter and Demer, 2008; McClatchie, 2009). Sampling of such skewed distributions is often the dominant component of variance in acoustic surveys

(Pennington, 1983; Demer, 2004). Acoustic surveys are therefore conducted along parallel-line transects which span the anticipated fish habitat. The survey design assumes the acoustic backscatter between the transects is independent and permits statistically-unbiased estimations of mean biomass densities and sampling variances for target species (Jolly and Hampton, 1990). Sampling error is minimized by increasing sampling effort, or, in cases where the areas of highest densities are known *a priori*, allocating most effort to these regions (Jolly and Hampton, 1990).

4. Data collection and treatment

Measurements of volume backscattering strength (S_v; dB re 1 m) and target strength (TS; dB 1 m^2) are made using calibrated, multi-frequency (typically 18, 38, 70, 120, and 200 kHz) echosounders (Simrad EK60) configured with split-beam transducers (typically Simrad ES18-11, ES38B, ES70-7C, ES120-7C, and ES200-7C, respectively).

Throughout the survey, the echosounders synchronously transmit 1024-μs pulses every 0.5 s, to allow multiple insonifications of small fish schools at the nominal survey speed of 10 kts. The transmit powers are 2000, 2000, 1000, 500, and 100 W at 18, 38, 70, 120, and 200 kHz, respectively. Following each transmission, the echo power data are recorded for periods corresponding to an observational depth of 250 m. These acoustic data are indexed by time and geographic position using navigational data from a GPS receiver input to the echosounder software (Simrad ER60). The survey-depth range accommodates the maximum of the expected sardine-depth distribution (i.e., ca. 70 m depth), and that of other CPS and krill (**Table 1**).

Using post-processing software (Myriax Echoview), the echo power values are compensated for propagation losses (spherical spreading and attenuation) and system parameters (transmit wavelength, pulse duration, and power; and transducer gain and equivalent two-way beam angle), and converted to volume backscattering coefficients (s_v; m^{-1}) and volume backscattering strengths ($S_v = 10 \log (s_v)$; dB re 1 m^{-1}). The latter is plotted versus depth and trackline distance, an 'echogram', to provide high-resolution imagery of backscatter density and depth distribution.

5. Analytical procedure

In addition to echoes from sardine, there are potentially echoes resulting from other CPS such as northern anchovy (*Engraulis mordax*), jack mackerel (*Trachurus symetricus*), Pacific mackerel (*Scomber japonicus*), Pacific herring (*Clupea pallasi*), and Pacific saury (*Cololabis saira*); semi-demersal fish such as Pacific hake (*Merlucius productus*); and krill (principally *Euphausia pacifica* and *Thysanoessa spinifera*). When analyzing the acoustic survey data, it is therefore necessary to objectively filter 'acoustic by-catch', backscatter not from the target species, e.g., sardine. **Table 1** summarizes some relevant features of by-catch candidates, with attention to their geographic and depth distributions, maximum lengths, schooling and diel vertical migration (DVM) behaviors, and food preferences.

Objective identification of echoes from CPS, i.e. epi-pelagic fish with swimbladders, is performed using a semi-automated data-processing algorithm (detailed below and illustrated in **Fig. 2)**. Background noise is estimated for each echosounder frequency and subtracted from the respective echograms of S_v. Portions of the 'noise-reduced' echograms are designated 'bad data' if the associated vessel speed is below a threshold, i.e. five kts, indicating it was 'on station' or otherwise 'off effort'.

The S_v values in these speed-filtered echograms are preliminarily identified as echoes from fish with swim bladders if their variance-to-mean-ratio (Demer *et al.*, 2009) is within a certain range (i.e., -60 dB $\leq$ *VMR* < -16 dB). The S_v values outside this *VMR* range are set to -999 dB (practically zero).

The '*VMR*-filtered' echograms (**Fig. 2a)** are gridded into ten-sample-deep by three-transmission-long bins. The S_v values within each depth-distance window are replaced by the median value of the S_v ensemble. The resulting data are then re-sampled to their original resolution. This procedure reduces the variance of the stochastic data and allows comparisons of the median S_v values with expected ranges of values for the target species.

The 'median-filtered' echograms (**Fig. 2b**) are compared to predictions of backscattering spectra for CPS, their backscatter versus frequency. The echograms are ultimately apportioned to CPS, and all else, using the following ranges of S_v differences: $-12 \leq S_{v18\,\mathrm{kHz}} - S_{v38\,\mathrm{kHz}} \leq 20.5$; $-17 \leq S_{v70\,\mathrm{kHz}} - S_{v38\,\mathrm{kHz}} \leq 10$; $-17 \leq S_{v120\,\mathrm{kHz}} - S_{v38\,\mathrm{kHz}} \leq 14$; and $-14 \leq S_{v200\,\mathrm{kHz}} - S_{v38\,\mathrm{kHz}} \leq 5$ dB, and a requirement that the maximum S_v at 38 kHz in five-m deep by 100-m distance cells must exceed -43 dB. For pixels which do not meet all these criteria, their corresponding S_v values in the noise-free echograms are set to -999 dB. The resulting 'CPS' echograms (**Fig. 2c)** are thresholded below S_v = -60 dB, which corresponds to a density of approximately three fish•100 m^{-3}, in the case of 20-cm-long sardine. The s_v values are then summed and averaged within each five-m depth by 100-m distance cell between an observational range of approximately 10 and 70 m depth (**Fig. 2d**), or, if the seabed is shallower, to three m above the estimated dead zone (Demer *et al.*, 2009). The resulting s_A values, attributed to CPS, are then apportioned to species using trawl data. However, consideration must be given to the time-of-day the acoustic samples were taken.

Most CPS exhibit diel vertical migrations (**Table 1**); they school at depth during day and ascending to the surface to feed during night (Mais, 1974). Consequently, the probability of detecting echoes from sardine at night is low using downward-projecting echosounders. The night-time data is negatively biased (Cutter and Demer, 2008). Therefore, only the s_A values from the day-time portions of the surveys, i.e., the period between nautical twilights, are used to estimate the distributions and abundances of sardine and other CPS (**Fig 3 - 5**).

The daytime s_A values corresponding to CPS ($s_{A_{CPS}}$) are apportioned to *j* species present using the catch mixtures in the nearest (space and time) trawl samples (Nakken and Domasnes, 1975):

(1)

where w_i is the proportion of the mass of the catch (kg) for the *i*-th species, and $\langle TS_i \rangle$ is its length-weighted mean target strength (*TS*; dB re 1 $m^2 \cdot kg^{-1}$). In other words, each $\langle TS_i \rangle$ is a mean *TS* weighted by the *TL* distribution of the sampled fish of that species. The *TS* relationships employed are:

$$TS = -14.90 \times \log(TL) - 13.21, \text{ for sardine;} \quad (2)$$

$$TS = -12.15 \times \log(TL) - 21.12, \text{ for anchovy; and} \quad (3)$$

$$TS = -15.44 \times \log(TL) - 7.75, \text{ for mackerel,} \quad (4)$$

where *TL* (cm) is the total length of the fish. These relationships were originally estimated for anchovy (*Engraulis capensis*), sardine (*Sardinops ocelatus*), and horse mackerel (*Trachurus trachurus*), based on the combination of backscatter-versus-length and mass-versus-length measurements of *in situ* fish (Barange *et al.*, 1996). Because Pacific mackerel and jack mackerel have similar *TS* (Peña, 2008), eq. (4) is used for both of these species. The s_A values are converted to fish-biomass density (ρ_i; kg·nautical mile^{-2}) using:

$$\rho_i = \frac{s_{A_i}}{4\pi 10^{\left(\langle TS_i \rangle /10\right)}}. \quad (5)$$

The sampling variances are estimated using bootstrapping procedures (Efron, 1981) that provide better statistical inference than traditional methods (Jolly and Hampton, 1990) for small sample sizes. Confidence intervals for the mean biomass densities are estimated by constructing 1,000 bootstrap samples (sets of equal size as the original set and resampled with reposition) of the transects and calculating the respective survey means (weighted averages using transect lengths as weights). In each iteration, one trawl is randomly removed and the biomass is calculated without it to evaluate the variability of species-classification and length-distribution error. The confidence intervals for the survey mean are estimated as the 2.5 % and 97.5 % percentiles of the bootstrap-survey-mean distribution. The standard error is given by the standard deviation of the bootstrap means. The coefficient of variation (CV) is estimated by dividing the standard error by the mean of the bootstrap survey means (Efron, 1981).

III. Lessons Learned from Application

1. Method conditions met?

Uncertainty in any estimate includes systematic and random components of measurement and sampling error. The precisions of acoustic survey results are mostly influenced by random sampling error (Demer, 2004). The accuracies of the survey results are effected mostly by temporally- and spatially-variable, systematic measurement and sampling errors. Examples of the latter include variable biases due to animal behavior (e.g. geographic and diel vertical migrations); target identification; and changes in *TS* versus changes in target morphology, orientation, and depth (Demer, 2004). Temporally- and spatially-varying biases in acoustic biomass estimates can confound observations of change in abundance.

In addition to large geographic migrations, CPS follow diel cycles in schooling behaviour and vertical position in the water column (Blaxter and Hunter, 1982). At night, they tend to migrate towards the sea surface (Neilson and Perry, 1990) and disperse. Even during the day, however, CPS may aggregate near the sea surface (Fréon and Misund, 1999), making it difficult to detect them using hull-mounted, vertically-directed echosounders (Cutter and Demer, 2008). Moreover, sardine schools located near to the sea surface may dive or swim horizontally away from the survey vessel, also causing negative bias to the survey results (Cutter and Demer, 2008). However, *TS* of diving fish may be reduced relative to that of naturally-oriented fish (Cutter and Demer, 2007), resulting in a positive bias. The data from the ME70 may help to mitigate these sources of uncertainty (Demer *et al.*, in prep) by providing a much large observational volume, perhaps to 100-s of m the sides of the survey vessel, and near to the sea-surface.

Objective echo-classification procedures are required for analyses of acoustic survey data. Most contemporary methods exploit frequency response, which is mainly a function of the animal size, shape, and morphology, and the acoustic frequencies and incidence angles. Frequency response is useful to separate plankton backscatter from that of fish schools and distinguish between backscatter from swimbladdered and non-swimbladdered fish (Korneliussen and Ona, 2002). Differences in frequency responses due to the shapes and sizes of internal organs, especially the swimbladder (Whitehead and Blaxter, 1989), may also allow remote species discrimination. For example, Conti and Demer (2003) found differences in the frequency responses of Pacific sardine and northern anchovy. Such data can be used to validate physics-based scattering models (e.g., Conti and Demer, 2003; Renfree *et al*., 2009), which can be used to better predict *TS* as a function of frequency and orientation (e.g., Cutter and Demer, 2007; Cutter *et al*., 2009).

TS is a stochastic variable which varies non-linearly (Demer and Martin, 1995) with animal size, shape, and morphology, i.e., the gonad size, stomach fullness, or proportion of flesh, fat, and bone (Ona, 1990); and the acoustic frequency and angle of incidence (Foote, 1980b). For CPS, the gas-filled swimbladder contributes mainly to its *TS* (Foote, 1980a). However, backscatter from the swimbladder can be reduced with changes in the acoustic incidence angle and reduction of swimbladder volume (e.g. with increasing pressure at larger depths). Unfortunately, there are no published studies of *TS* of *in situ* Pacific sardine, northern anchovy, Pacific mackerel, or jack mackerel in the CCE. Until such measurements are made, it is necessary to use the *TS*-to-length models estimated from measurements of similar species in another ecosystem (Barange *et al*., 1996).

2. Operational conditions met?

Recent assessments of sardine biomass, considering the DEPM results, range from 1.3 Mt in 2006 to 0.7 Mt in 2008 (**Table 2;** Hill *et al*., 2009). Using the aforementioned acoustic-trawl survey method, the total biomass of sardine in the northern stock was estimated from the summer 2008 survey to be 0.8 Mt with a CV of 29 % (**Table 3**). As predicted for the summer months by the sardine habitat model (Zwolinski *et al*., submitted), the sardine biomass was located mostly off the coasts of Oregon and Washington (**Fig. 4**). The biomasses (**Table 3**) and distributions of Pacific mackerel (**Fig. 5)** and jack mackerel (**Fig. 6**) were also estimated using the same method.

3. Past peer-review advice for improvement

The aforementioned acoustic-trawl method is to be reviewed by the Center for Independent Experts (CIE) in early 2011. If deemed appropriate, the results from the 2006, 2008, and 2010 coastwide surveys will be considered in the stock assessment model later that year and presented to the Pacific Fisheries Management Council for their consideration.

IV. Workshop Recommendations for Surveys to Enhance Stock Assessments

1. Opportunities for collaboration

Fishery-catch data, collected proximate in space and time to the acoustic survey, can be used to: improve the apportioning of s_A to species. It can also be used to weight $<TS_i>$ by *TL* for the various species. It is therefore beneficial to conduct acoustic surveys for sardine during the summer months when sardine are located, and the fishery occurs, off northern California, Oregon, and Washington.

Methods for species identification and *TS* estimation can be improved through collaborative investigations involving aerial, acoustic, and net sampling. After a fish school is spotted from an aircraft, and before it is netted, a vessel equipped with multi-frequency echosounders and a multi-beam sonar, optimally the ME70, will drive around the school to acoustically estimate its size and shape; and then drive over the school multiple times to acoustically estimate the fish school depth and density. The data from the subsequent purse-seine catch will be used to estimate the biomasses and *TL*-distributions by species. These data will be used to validate physics-based scattering models for improved target identification and *TS* estimation.

2. Linkage to other methods

Acoustic-trawl surveys can provide efficient, precise, accurate estimates of sardine distribution and abundance. The same data can be used to estimate the distributions and abundances of other CPS and their zooplankton prey. Surveys of sardine may be most efficiently conducted during the months of June and July, when the habitat is compressed along the coasts of Oregon and Washington, the fish are generally north of Point Conception and south of the Strait of Juan de Fuca, the daytime survey effort is maximized, and the data analysis can be augmented with fishery catch data from the same general time and place. Improvements to survey variance may result from further constraining the survey to areas containing fish, as identified from aerial observations (Churnside *et al.*, 2009). Improvements to survey accuracy will result from improvements to acoustic-target identification and target strength estimation as described above.

References

Barange, M., Hampton, I., and Soule, M. 1996. Empirical determination of in situ target strengths of three loosely aggregated pelagic fish species. – ICES Journal of Marine Science, 53: 225–232.

Blaxter J., Hunter J. 1982. The biology of the clupeoid fishes. Advances in Marine Biology 20: 1–223

Churnside, J.H., Demer, D.A., Griffith, D., Emmett, R.L., and Brodeur, R.D. 2009. “Comparisons of Lidar, acoustic and trawl data on two scales in the Northeast Pacific Ocean,” *CalCOFI Reports* 50: 118-122.

Conti, S. G., and Demer, D. A. 2003. Wide-bandwidth acoustical characterization of anchovy and sardine from reverberation measurements in an echoic tank. – ICES Journal of Marine Science, 60: 617–624.

G.R. Cutter Jr. and D.A. Demer, “Accounting for scattering directivity and fish behavior in multibeam-echosounder surveys,” *ICES J. Mar. Sci.*, 64(9): 1664-1674 (2007).

Cutter Jr., G.R. and Demer, D.A. (eds) 2008, California current ecosystem survey 2006. Acoustic cruise reports for NOAA FSV Oscar Dyson and NOAA FRV David Starr Jordan. U.S. Dep. Commer., NOAA Tech. Memo., NOAA-TM-NMFS-SWFSC-415, 98 pp

Cutter, G. R., Renfree, J. S., Cox, M. J., Brierley, A. S., and Demer, D. A. 2009. Modelling three-dimensional directivity of sound scattering by Antarctic krill:

progress towards biomass estimation using multibeam sonar. – ICES Journal of Marine Science, 66: 1245–1251.

Demer, D. A. 2004. An estimate of error for the CCAMLR 2000 survey estimate of krill biomass. Deep Sea Research II, 51: 1237–1251

Demer D.A. and Martin L.V. (1995) Zooplankton target strength: volumetric or areal dependence? Journal of Acoustical Society of America 98: 1111–1118

Demer, D.A., Cutter, G.R., Renfree, J.S., and Butler, J.L. 2009 "A statistical-spectral method for echo classification". *ICES Journal of Marine Science*, 66: 1081–1090.

Demer, D.A., Cutter, G.R., Renfree, J.S., Weber, T.C., Stienessen, S., and Wilson, D., in-prep. Characterization of pelagic scatterers using multibeam echosounder data: echo amplitude and phase, and their variabilities and frequency spectra.

Efron, B. 1981.Nonparametric Standard Errors and Confidence Intervals. The Canadian Journal of Statistics, 9: 139-158

Fréon P., Misund O. Dynamics of Pelagic Fish Distribution and Behaviour: Effects on Fisheries and Stock Assessment. (1999) Oxford: Blackwell Science

Foote, K. G. 1980a. Importance of the swimbladder in acoustic scattering by fish: A comparison of gadoid and mackerel target strengths. The Journal of the Acoustical Society of America 67: 2084-2089.

Foote, K. G. 1980b. Effect of fish behaviour on echo energy: the need for measurements of orientation distributions. Journal du Conseil International pour l'Exploration de la Mer, 39: 193–201

Hill, K. T., Lo, N. C. H., Macewicz, B. J., Crone P. R. and Felix-Uraga, R. 2009. Assessment of the Pacific sardine resource in 2009 for U.S. management in 2010. DRAFT Report for PFMC Review

Holliday, D.V. 1972, Resonance structure in echoes from schooled pelagic fish, *Journal of the Acoustical Society of America* 51: 1322–1332.

Jolly, G.M. and Hampton, I. 1990. A stratified random transect design for acoustic surveys of fish stocks. Canadian Journal of Fisheries and Aquatic Sciences 47: 1282-1291.

Korneliussen R. J., Ona E. 2002. An operational system for processing and visualizing multi-frequency acoustic data. ICES Journal of Marine Science 59:293–313.

Mais, K. 1974. Pelagic fish surveys in the California Current. Bull. Dep. Fish Game St. Calif., 162: 1-79.

Mais, K. 1977. Acoustic surveys of northern anchovies in the California Current System, 1966-1972, Rapp. P.-v Reun. Cons. Int. Explor. Mer, 170:287-295.

McClatchie, S. (ed) 2009. Report on the NMFS California Current Ecosystem Survey (CCES) (April and July-August 2008). *U.S. Dep. Commer., NOAA Tech. Memo*., NOAA-TM-NMFS-SWFSC-438, 98 pp

Nakken, O. and Dommasnes, A. 1975. The application of an echo integration system in investigations of the stock strength of the Barents Sea capelin 1971-1974. ICES CM 1975/B:25, 20 pp. (mimeo).

Neilson J., Perry R. 1990 Diel vertical migration of marine fishes: an obligate or facultative process? Advances in Marine Biology 26:115–168

Ona E. 1990. Physiological factors causing natural variations in acoustic target strength of fish. J mar biol Ass UK 70:107-127.

Peña, H., 2008. In situ target-strength measurements of Chilean jack mackerel (*Trachurus symmetricus murphyi*) collected with a scientific echosounder installed on a fishing vessel. ICES Journal of Marine Science, 65: 594–604

Pennington, M. 1983. Efficient estimators of abundance for fish and plankton surveys. Biometrics 33: 281–286.

Renfree, J. S., Hayes, S. A., and Demer, D. A., 2009. Sound-scattering spectra of steelhead (*Oncorhynchus mykiss*), coho (*O. kisutch*), and Chinook (*O. tshawytscha*) salmonids. ICES Journal of Marine Science, 66: 1091–1099.

Smith, P.E., 1978. Precision of sonar mapping for pelagic fish assessment in the California current. Journal du Conseil International pour l'Exploration de la Mer, 38: 33-40

Whitehead, P., and Blaxter, J. 1989. Swimbladder form in clupeoid fishes. Zoological Journal of the Linnean Society, 97: 299–372.

Wood, S. 2006. Generalized additive models: an introduction with R 1st Edition. Texts in Statistical Sciences. Chapman & Hall CRC.

Zwolinksi, J. P., Emmett, R. L., and Demer, D. A., submitted. Predicting habitat to optimize sampling of Pacific sardine (*Sardinops sagax*), Canadian Journal of Fisheries and Aquatic Sciences.

Tables

Table 1. Geographic and depth distributions, maximum total length, schooling and diel vertical migratory (DVM) behaviours, and food preferences for sardine and candidate acoustic 'by-catch' in the CCE.

Species	South-north distribution	East-west distribution	Depth distribution (generally)	Max. *TL*	Schooling / Diel vertical migration	Prey	References
Pacific sardine	Gulf of California to the Gulf of Alaska	Coastal and oceanic; larger fish to 300 nautical miles offshore	0 - 100 m (0 - 50 m)	30 cm	Dense schools / Strong DVM	Phyto- and zooplankton	Mais, 1974; Blaxter and Hunter, 1982
Northern anchovy	Baja California to Canada (discrete locations)	Coastal	0 – 200 m	25 cm	Dense schools / Strong DVM	Phyto- and zooplankton, (typically larger than sardine prey)	Miller and Lea, 1972; Mais, 1974
Pacific mackerel	Baja California to the Gulf of Alaska	Coastal and oceanic	0 – 300 m (0 - 50 m)	40 cm	Dense schools / Strong DVM	Large zooplankton and small fish	Fitch, 1958; Gluyas-Millán and Quiñones-Velásquez, 1997
Jack mackerel	Baja California to the Gulf of Alaska	Coastal and oceanic; larger fish to 1000 nautical miles	0 - 300m (0 - 50 m)	60 cm	Dense schools and solitary / Strong DVM	Large zooplankton, small fish, and squid	Mais, 1974; MacCall and Stauffer, 1983

		offshore					
Pacific herring	Northern Baja California to Alaska (discrete locations)	Neritic and coastal	0 – 200 m	30 cm	Dense schools and solitary / Strong DVM	Zooplankton	Lassuy, 1989
Pacific hake	Baja California to the Gulf of Alaska	Coastal and oceanic; larger fish further offshore	0 - 600 m	90 cm	Diffuse aggregations / Weak DVM	Large zooplankton and small fish	Alverson and Larkins, 1969; Mais, 1974; Quirollo, 1992;
Pacific saury	Central and Northern California	Oceanic	0 - 250m	30 cm	Dense schools / Strong DVM	Zooplankton	Mais, 1974

Table 2. Biomasses (Mt) of: total epi-pelagic fishes with swimbladders located shallower than 70 m depth and estimated acoustically; total sardine located off southern California and estimated using the DEPM; and total sardine estimated using an assessment model with input from the DEPM surveys.

<table>
<tr><th>Year</th><th>Season</th><th>Area - Acoustics</th><th>CPS - Acoustics</th><th>Sardine - DEPM</th><th>Sardine - Assessment</th><th>References</th></tr>
<tr><td>2006</td><td>Spring</td><td>Coastwide</td><td>2.0 Mt (CV=18.7 %)</td><td rowspan="2">1.3 Mt (CV=47 %)</td><td rowspan="2">1.3 Mt</td><td rowspan="2">Cutter and Demer (2008); Hill et al. (2009)</td></tr>
<tr><td>2006</td><td>Spring</td><td>CalCOFI</td><td>2.1 Mt (CV= 19.7 %)</td></tr>
<tr><td>2008</td><td>Spring</td><td>Northern CCE</td><td>0.4 Mt (CV=44.6 %)</td><td rowspan="2">0.1 Mt (CV=43 %)</td><td rowspan="2">0.8 Mt</td><td rowspan="2">McClatchie (2009); Hill et al. (2009)</td></tr>
<tr><td>2008</td><td>Summer</td><td>Coastwide</td><td>1.38 Mt (CV=17.9 %)</td></tr>
</table>

Table 3. Biomass estimates (Mt) and their coefficient of variation (CV) values for CPS in the CCE during the 2008 survey. The total biomasses are apportioned two strata as defined in **Figs. 3-5**. Catches of other CPS were too few to enable estimations of their biomasses.

Species	Stratum 1	Stratum 2	Total
Pacific sardine	0.736 (31 %)	0.069 (84 %)	0.805 (29 %)
Jack mackerel	0.644 (32 %)	0.083 (80 %)	0.727 (30 %)
Pacific mackerel	0.022 (55 %)	-	0.022 (55 %)
Northern anchovy	0.014 (57 %)	0.108 (69 %)	0.122 (62 %)

Figures

Figure 1. Seasonal distribution of the potential habitat of adult sardine in the CCE (Zwolinski *et al.*, submitted). Optimal habitat includes 80 % of the positive samples during the 1989 to 2009 surveys. Optimal plus good habitat includes 90 % of the positive samples; optimal plus good plus bad habitat includes 99 % of the positive samples; and unsuitable habitat includes < 1 % of the total positive samples not included in the other classes. The model accurately predicts the habitat of sardine, irrespective of their spawning condition.

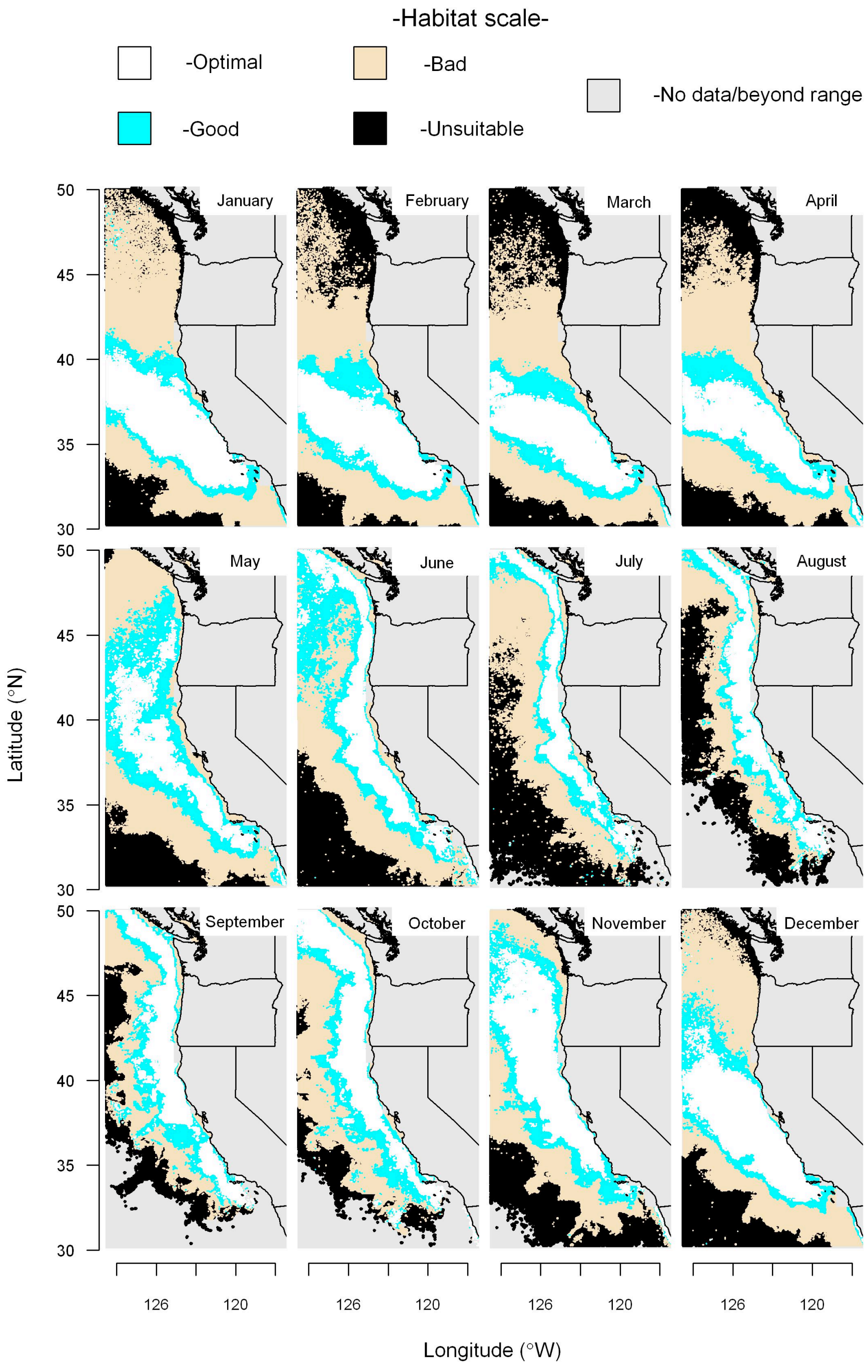

Figure 2. Echograms of 38 kHz S_v (dB re 1 m^{-1}), zero to 250 m depth by ca. one km distance, illustrating the algorithm for identification and integration of echoes from CPS: (**a**) *VMR*-filtered; (**b**) median-filtered; (**c**) candidate CPS; and (**d**) candidate CPS shallower than 70 m depth with five-m depth by 100-m distance cells. The s_v (m^2·nautical mile^{-2}) attributed to epi-pelagic CPS are integrated for each cell and apportioned to species using trawl-catch data.

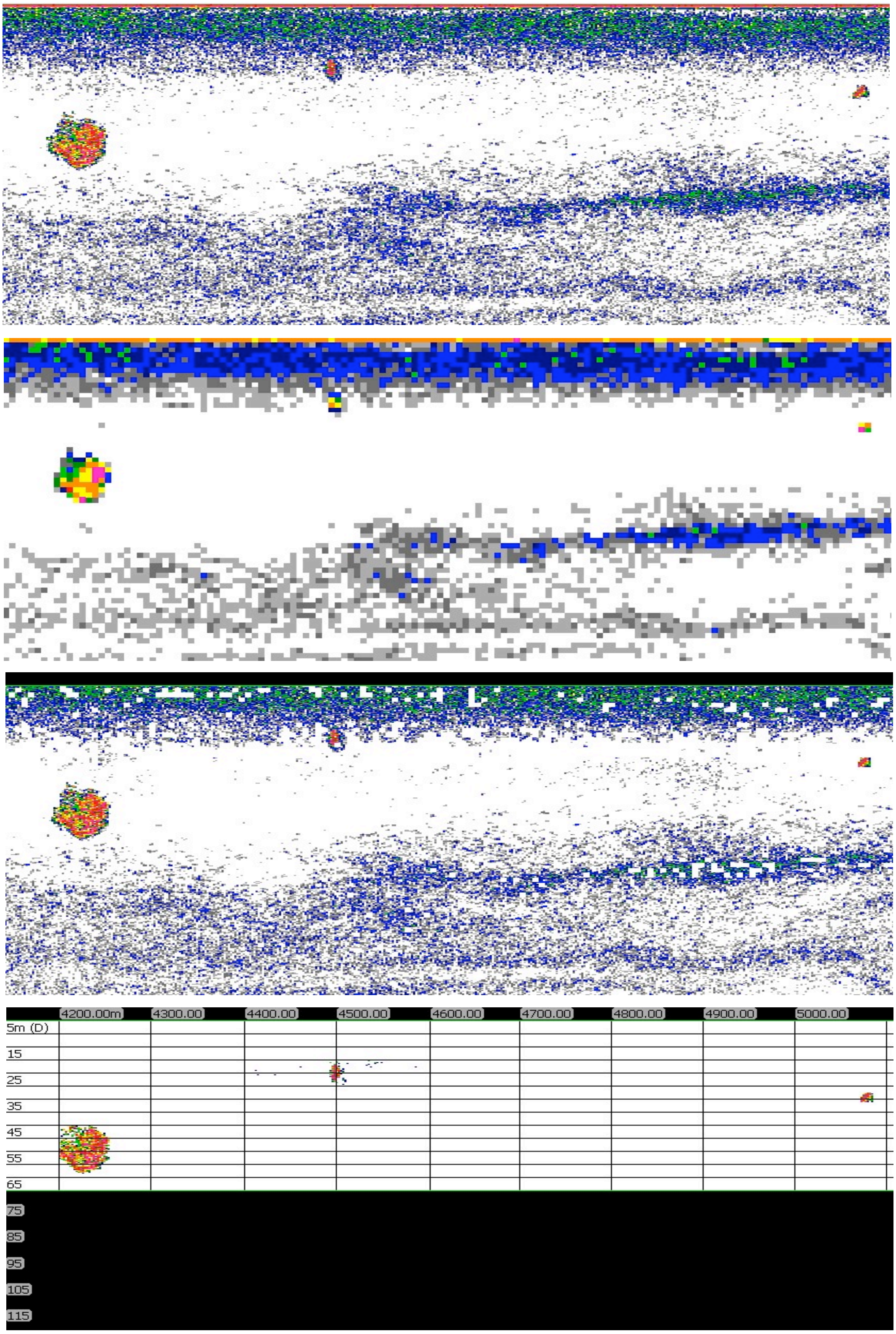

Figure 3. Distribution of sardine densities during summer 2008.

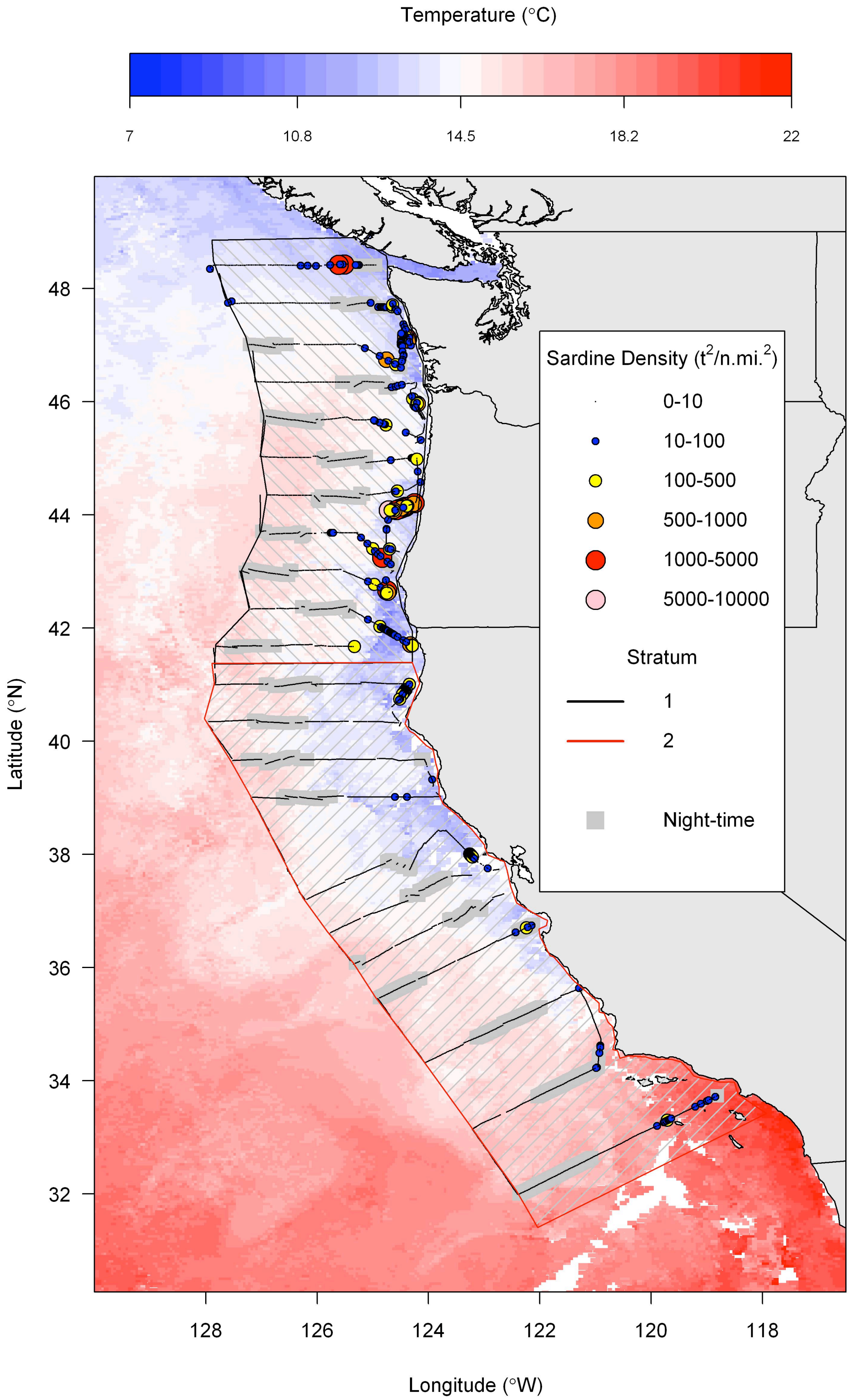

Figure 4. Distribution of Pacific mackerel densities during summer 2008.

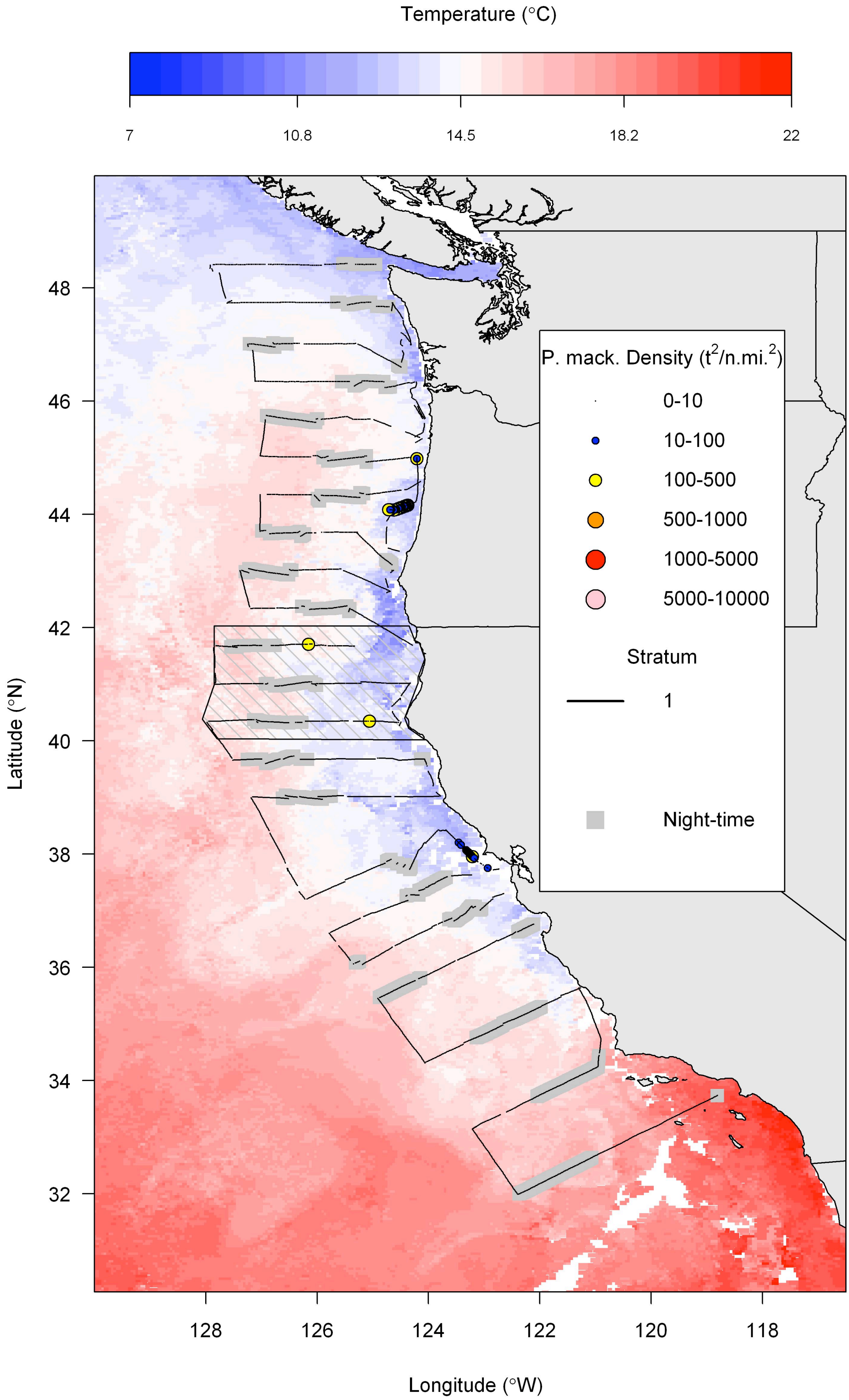

Figure 5. Distribution of jack mackerel densities during summer 2008.